Healthy Aging and Visual Working Memory

Healthy Aging and Visual Working Memory: The Effect of Mixing Feature and Conjunction Changes

Stephen Rhodes[1], Mario A. Parra[1,2], Nelson Cowan[3], and Robert H. Logie[1]

[1]Human Cognitive Neuroscience, Centre for Cognitive Ageing and Cognitive Epidemiology, Department of Psychology, University of Edinburgh

[2]Department of Psychology, Heriot-Watt University

[3]Department of Psychological Sciences, University of Missouri

Draft date: December 5, 2016. Word count (excluding references) = ????

Author Note

This work was supported by a PhD studentship from The University of Edinburgh Centre for Cognitive Ageing and Cognitive Epidemiology, part of the UK cross council Lifelong Health and Well-being Initiative (MR/L501530/1). Funding from the Biotechnology and Biological Sciences Research Council (BBSRC) and Medical Research Council (MRC) is gratefully acknowledged. MAP's work is supported by Alzheimer's Society, Grants AS-R42303 and AS-SF-14-008. Part of this work was presented at the 55th annual meeting of the Psychonomic Society, Long Beach, USA (2014) and at the 2nd International meeting of the Psychonomic Society in Granada, Spain (2016). The first author is now at the Department of Psychological Sciences, University of Missouri, USA. Email: rhodessp@missouri.edu.

Abstract

It has been suggested that an age-related decline in the ability to bind and retain conjunctions of features may account for some of the pronounced decline of visual working memory across the adult life-span. So far the evidence for this suggestion has been mixed with some suggesting a specific deficit in binding to location, while the retention of surface feature conjunctions (e.g. color-shape) appears to remain largely intact. The present experiments follow up on the results of an earlier study finding that older adults were specifically poor at detecting conjunction changes when they were mixed with trials containing changes to individual features, relative to when these trials were blocked (Cowan et al., 2006, *Dev. Psychol., 42*, pp. 1089). Using stimuli defined by conjunctions of color and shape (Experiment 1), and color and location (Experiment 2) we find no evidence that older adults are less accurate at detecting binding changes when trial types are mixed. Further, analysis of estimates of discriminability provides substantial-to-strong evidence *against* this suggestion. We discuss these findings in relation to previous studies addressing the same question and suggest that much of the evidence for specific age-related VWM binding deficits is not as strong as it first appears.

Keywords: Visual Working Memory, Change Detection, Cognitive Aging, Feature Binding

Healthy Aging and Visual Working Memory: The Effect of Mixing Feature and Conjunction Changes

In the literature on source memory deficits in long-term memory an influential suggestion has been that older adults specifically struggle to bind distinct elements of an episode together (Naveh-Benjamin, 2000). Indeed studies using a variety of stimuli, from pairs of unrelated words to pictures of faces and scenes, have convincingly shown that age differences in recognition performance are disproportionately large for pairs of items relative to the items individually (see Old & Naveh-Benjamin, 2008, for a review and meta-analysis). The success of this account in the long-term memory realm has led to the suggestion that binding deficits may account for age-related change to working memory. In particular, researchers (Brockmole, Parra, Della Sala, & Logie, 2008; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Sander, Lindenberger, & Werkle-Bergner, 2012) have become interested in whether a deficit in binding together the basic features of objects (e.g. color, shape, location) can account for some of the pronounced decline of visual working memory (VWM) observed across the life-span (e.g. Brockmole & Logie, 2013; Johnson, Logie, & Brockmole, 2010). However, in contrast to the pronounced between-item associative deficit observed in long-term memory—and more recently in working memory (Chen & Naveh-Benjamin, 2012; Peterson, Schmidt, & Naveh-Benjamin, 2017)—the evidence concerning this within-object 'level of binding' (Zimmer, Mecklinger, & Lindenberger, 2006) has been less clear (though see Peterson & Naveh-Benjamin, 2016).

It has been proposed that features of items that are present at the same time in the focus of attention are likely to be bound together to form a new complex in long-term memory, in contrast to features or items that are not in the focus of attention at once (e.g., Cowan, Donnell, & Saults, 2013). According to that logic, one potential source of the long-term memory deficit in within-object binding is a deficit in the ability to form these kinds of binding in the first place, in the core attention-demanding part of working memory. If, however, older adults show no deficit in binding of features within a visual object (in our experiments, color to shape and color to location), then

researchers will have to look elsewhere for the source of the long-term deficits, such as in the mechanisms of long-term memory consolidation.

Evaluating the Evidence for Age-Related VWM Binding Deficits

Mitchell and colleagues were the first to assess the effect of age on the retention of feature bindings in working memory in a series of experiments (Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Mitchell, Johnson, Raye, & D'Esposito, 2000). In these experiments they presented younger and older participants with a sequence of three nameable clip-art-like objects (for 1 second each) on a 3×3 grid and then, following an 8.5 second delay, probed memory for the object, location, or object-location pairing in separate blocks. They found significant age differences in performance when the task required maintenance of object-location conjunctions, whereas there was no significant age difference in tasks assessing memory for the individual components. These findings have been taken to indicate that older adults have a specific difficulty in maintaining 'what was where' in VWM.

However, upon further consideration, these findings are not as convincing as they first appear. Namely, reporting a significant age difference in one condition and not in another is not evidence for a *disproportionate* effect of age in that condition; this requires a test of the age-group by condition interaction (see Gelman & Stern, 2006; Nieuwenhuis, Forstmann, & Wagenmakers, 2011). Crucially, in the behavioral experiments of Mitchell, Johnson, Raye, Mather, and D'Esposito (2000) this interaction was *not* significant by conventional standards ($p = 0.06$ and 0.13 for Experiments 1 and 2, respectively). The interaction test is not reported in the fMRI study of Mitchell, Johnson, Raye, and D'Esposito (2000), however the t-test of the age difference in the object-location condition did not reach conventional levels of significance ($t(10) = 2.07$, $p = 0.06$. See pp. 199) so it is unlikely that the interaction was present in this case. Thus it appears that in these studies there was actually no clear evidence that age disproportionately affects binding to location in VWM. Evidence for crucial interactions is also missing from more recent studies that have been cited in support of VWM

binding deficits (Borg, Leroy, Favre, Laurent, & Thomas-Antérion, 2011; Fandakova, Sander, Werkle-Bergner, & Shing, 2014).

Other recent studies have been more equivocal on this issue. In two experiments, Read, Rogers, and Wilson (2016) found that the effect of age on change detection was not clearly larger for discriminating feature (color or shape) to location binding changes relative to changes to these features individually. On the other hand, also in two experiments, Peterson and Naveh-Benjamin (2016) presented colored shapes in different locations and found a slightly larger age-effect on change detection performance for the binding of object and location relative to object or location alone. Using a recall task, Peich, Husain, and Bays (2013) found that older adults were more likely than younger adults to re-locate a previously seen feature (color or orientation) to a location that was occupied by a different feature; that is, older adults were more likely to commit so-called 'mis-binding' errors. However, following up on this, Pertzov, Heider, Liang, and Husain (2015) have suggested that once age differences in the recall of the features themselves are accounted for, older adults do not commit any more mis-binding errors than younger adults. In summary, the literature following the early findings of Mitchell and colleagues has been somewhat mixed but in general suggests little-to-no additional age-related binding deficit when location is concerned.

Studies assessing the binding between *surface features* (e.g. shape and color), as opposed to the binding of features to location, have more clearly suggested that there is no disproportionate VWM deficit for conjunctions of features over and above the general drop in performance observed for the component features (provided that the influence of potential verbal strategies is minimized, either via the use of difficult to name stimuli or concurrent suppression, Brockmole et al., 2008; Brown, Niven, Logie, Rhodes, & Allen, 2016; Isella, Molteni, Mapelli, & Ferrarese, 2015; Parra, Abrahams, Logie, & Della Sala, 2009; Peterson & Naveh-Benjamin, 2016; Rhodes, Parra, & Logie, 2016). While some have reported age by condition interactions these either go against the expectation of an age-related binding deficit (Brown et al., 2016, Experiment 3) or have failed to replicate (Brown & Brockmole, 2010; Brown et al., 2016; Rhodes et al.,

2016). Thus the weight of evidence, so far, appears to support the *absence* of an age-related binding deficit for surface features.

In light of the pronounced associative deficit in long-term memory (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008) and working memory (Chen & Naveh-Benjamin, 2012; Peterson et al., 2017), the lack of a binding deficit for within object features in VWM is perhaps surprising. However there are reasons to predict differential effects of age on these theoretically different levels of binding (see Zimmer et al., 2006, for discussion). Firstly between-item, or relational, binding appears to be heavily dependent on the hippocampus in both working memory (Parra et al., 2015; Piekema, Rijpkema, Fernández, & Kessels, 2010) and long-term memory (Staresina & Davachi, 2010), and the effects of healthy aging in terms of volumetric changes and white matter hyperintensities are especially pronounced in this region (Raz & Rodrigue, 2006; Yang, Goh, Chen, & Qiu, 2013). By contrast retaining the binding of color and shape does not appear to rely on the hippocampal formation (Parra, Della Sala, Logie, & Morcom, 2014; Parra et al., 2015). Secondly the binding of feature conjunctions in VWM appears to proceed relatively automatically (e.g. Allen, Baddeley, & Hitch, 2006), whereas the association of contextual, or extrinsic, attributes does not appear to proceed as obligatorily in working memory tasks (Ecker, Maybery, & Zimmer, 2013). Thus, as the effects of age tend to be reduced for relatively automatic processes (see Craik & Bialystok, 2006, for a review), we may predict the relational and conjunctive binding mechanisms to dissociate with age.

The apparent absence of a specific normal aging def for conjunctions of color and shape in change detection tasks becomes even more intriguing when paired with the large deficit observed in the early stages of Alzheimer's disease (e.g. Parra, Abrahams, Logie, & Della Sala, 2010). Consequently a great deal of effort has been devoted to identifying potential boundary conditions under which healthy older adults may struggle to retain conjunctions of surface features. Age differences in change detection performance have been assessed under conditions of increased attentional load (Brown & Brockmole, 2010), extended encoding duration (Brown et al., 2016; Rhodes et al.,

2016), or with potentially interfering information in the retention interval (Brown et al., 2016) and none of these manipulations have been found to specifically impair older adults' ability to detect conjunction changes. However the findings of one study in the literature (Cowan et al., 2006) point to another potential boundary condition, under which an age-related binding deficit may be observed, that has yet to be addressed in this context.

Motivation for the Present Experiments

Some of the strongest evidence that older adults may struggle to detect changes to conjunctions over features alone so far appears to come from the findings of Cowan et al. (2006). Using a change detection paradigm, Cowan et al. (2006) found that, when color-location conjunction change trials were mixed with changes to color only, there was a disproportionate effect of age on the detection of conjunction changes. Older adults showed an increased tendency to miss the conjunction changes. When these different trial types were presented in separate blocks, however, there was no clear age-related binding deficit. Thus mixing feature and conjunction changes may reveal specific age-related problems in maintaining and utilizing bound representations in VWM. Cowan et al. (2006) suggested that older adults were more likely to perform the change detection discrimination on the basis of probe familiarity which, in the mixed condition, would be sufficient to detect salient feature changes but not the less salient swaps of color and location. Relying only on familiarity in the blocked condition, on the other hand, would not support the detection of any changes, thus the older adults in this condition may have adopted a different criterion, or encoding/ retrieval strategies that improved their performance in the binding condition.

However, there are some potential issues with the paradigm used by Cowan et al. (2006) that warrant detailed discussion. In their study memory was probed by a single circled item in the test array with non-probed items also present, unchanged. Additionally, as the largest array size was ten, colors were selected from the set of seven *with* replacement, leading to the presence of duplicates in the arrays. Due to this a

color-location binding change in these experiments always introduced a duplicate into the test array, whereas a color change always introduced a unique color. When conditions were blocked this could have given the answer away to participants, therefore Cowan et al. (2006) ensured that on no-change trials in the binding condition the probe was always a duplicate and in the color only condition the unchanged probe was unique (see Cowan, Saults, & Blume, 2014, pp. 1826 for more detail). Thus in the binding condition it was sufficient to focus on duplicates and in the color condition to focus on unique colors. Age differences in apprehending this intricate aspect of the task might have contributed to age differences in performance. Further, it seems likely that noting which colors are duplicated in an array is a simpler task than noting which colors are unique. This would introduce a benefit for binding trials specifically when trials were blocked as opposed to mixed. This is evident in the Cowan et al. data (see Table 2 on page 1095), as there was a clear difference in terms of sensitivity (d') between the color and binding conditions in Experiment 1A in which these trials were mixed. In Experiment 2A, where trials were blocked, there was very little difference between the two conditions and, in fact, for younger adults sensitivity to binding changes was slightly better than that for color changes. So it may be that participants in the studies reported by Cowan et al. (2006) were able to use additional cues to guide the change detection decision that may have differentially benefited features and conjunctions, and have had a differential effect on older compared with younger participants.

In addition, the findings of Chen and Naveh-Benjamin (2012) cast doubt on a role of mixing versus blocking trials in the emergence, or exacerbation, of an age-related binding deficit. They used a continuous recognition paradigm in which participants studied a stream of face-scene pairs with interspersed tests of memory for items or associations following varying delays. The commonly observed associative deficit was no larger when item and associative trials were mixed together relative to when they were encountered in separate trial blocks. Given that, to our knowledge, only these two studies have directly addressed this issue the present experiments aimed to follow up on the findings of Cowan et al. (2006) by directly comparing, in younger and older healthy

adults, mixed and blocked trial lists for stimuli defined by conjunctions of color and shape (Experiment 1), and color and location (Experiment 2).

Experiment 1

In Experiment 1 we assessed the effect of mixing switches of color-shape conjunction with trials in which a brand new feature (color or shape) is introduced at test on older adults' change detection performance. There were a number of procedural changes between this study and the experiments of Cowan et al. (2006). Most notably during the test phase of our change detection task we only presented a single item with the non-probed items absent. We also only assessed two set sizes (3 and 6) meaning that we could sample features for each array without replacement. The absence of duplicates in the studied arrays and the absence of non-probed items in the probe displays avoids the potential inadvertent cues that were present in the paradigm of Cowan et al. (2006), which could have created an effect in that study due to strategic differences rather than binding differences. Of course another major difference between this experiment and that of Cowan et al. is that they assessed color-location binding whereas we looked at the binding of color and shape, a form that has appeared to be largely age-invariant in studies using a blocked design given our interest in potential boundary conditions on this. This is addressed in Experiment 2.

Method

Participants. Forty-eight younger adults from the student population of the University of Edinburgh took part in Experiment 1 in return for £5 for the 45 minute session. Forty-nine healthy older adults from the University of Edinburgh Psychology volunteer panel of members of the general public also took part and were offered £5 in return for participation. These groups were split between two conditions; one in which color, shape and color-shape conjunction changes were mixed together and another in which they were presented in separate trial blocks. Table 1 provides participants' demographic information. All older adults scored 27 or above on the MMSE.

Stimuli and Apparatus. Stimulus features were drawn from sets of 8 difficult to name colors and abstract polygons taken from Brockmole et al. (2008). Items in the memory array were constructed by selecting colors and shapes from these sets without replacement. Stimuli were presented on a grey background in 8 locations surrounding the center of the screen following an invisible circle (radius = 2.6°, at an approximate viewing distance of 50 cm). Objects measured approximately 1° visual angle and were separated center-to-center by at least 2°. The experiment was programmed using PsychoPy (Peirce, 2007) and presented over a 18" E96f+SB ViewSonic monitor with a resolution of 1024 × 768 and refresh rate of 100 Hz.

Design and Procedure. Prior to the main change detection task both groups completed the National Adult Reading Test (Nelson, 1982) to obtain an estimate of verbal-IQ (see Table 1) and a test of color vision (Dvorine, 1963). The older group also completed the Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975) prior to completing the main part of the experiment.

The general trial sequence of the change detection task is presented in Figure 1A along with examples of the kinds of trials presented to participants (Figure 1B). Participants initiated each trial by pressing the space-bar and following a 1000 ms fixation cross the memory array appeared for 900 ms. This was followed by a 1000 ms blank retention interval and then a single central probe item which remained present until a response was made. Finally, in line with the procedure of Cowan et al. (2006), participants were presented with feedback for 1000 ms in the form of a fixation cross that was colored green for a correct response or red otherwise.

Half of the trials presented to participants involved no-change as the probe was selected at random from the 3 or 6 objects presented. The remaining half of trials were split between color change, shape change, and binding change types (either blocked or mixed). A color change involved filling a previously seen shape with a color from outside the original memory set and a shape change involved presenting a new shape in a previously seen color. A binding change involved presenting combination of a color and shape from separate memory objects as the probe item (see Figure 1B). As

described above, participants in the blocked condition saw these changes in separate blocks with their own change trials, whereas participants in the mixed condition saw the three kinds of change trial interspersed with no-change trials.

The main experiment was split into 3 blocks with 32 change and 32 no-change trials each distributed evenly across the different set sizes. For the blocked condition all change trials in a given block were of a single type and for the mixed condition a change was equally likely to occur for color, shape, and binding. Participants in the blocked condition were given 6 practice trials looking for a particular kind of change before the corresponding block, whereas participants in the mixed condition were given 18 practice trials before the first block with all three kinds present. In the blocked condition the order of the three memory conditions (color, shape, binding) was fully counterbalanced.

Analysis. In their main analysis, Cowan et al. (2006) aimed to separate out the contribution of sensitivity and response bias to change detection accuracy and we aim to do the same. While they reported analyses of the (normal equal variance) signal detection theory measures, d' and c, in the present analysis we opt for P_r or 'corrected recognition' (Snodgrass & Corwin, 1988) and its associated bias measure, B_r. Selective influence studies have suggested that change detection with highly distinguishable, or supra-threshold, stimuli is mediated by discrete, all-or-nothing states rather than a graded continuous decision variable (Donkin, Tran, & Nosofsky, 2014; Rouder et al., 2008; although this may not characterize performance for more subtle changes, Keshvari, van den Berg, & Ma, 2013). Consequently, the high-threshold measure used here should better allow us to separate discriminability from bias. Nevertheless, in addition we also ran analysis with d' as the outcome measure; unless stated the P_r and d' analyses were in agreement.

Many previous reports of no additional binding cost with healthy aging (e.g. Brockmole et al., 2008; Brown & Brockmole, 2010; Isella et al., 2015) have been hampered by the fact that failure to reject the null, in and of itself, is not sufficient to argue *against* the presence of an age × condition interaction. Therefore in the present analysis of discrimination and bias metrics we opt for a model comparison approach

(see also, Brown et al., 2016; Rhodes et al., 2016). To obtain Bayes factors for the comparison of models defined by the presence or absence of specific main- or interaction-effects we use the default family of priors outlined by Rouder, Morey, Speckman, and Province (2012).

These data were analyzed using the `BayesFactor` package in `R` (Morey & Rouder, 2015; R Core Team, 2015). The analysis proceeded by comparing a full model, with all possible main effects and interactions, to reduced models omitting a single component at a time[1]. The resulting Bayes factors (B) reflect the weight of evidence in favor of *omitting* the component in question from the full model. Consequently a $B < 1$ implies evidence in favor of the effect, whereas a $B > 1$ denotes evidence against inclusion of the effect in the full model. Bayes factors have a simple interpretation (i.e. the reduced model is B times as likely as the full model given the data and priors) without necessary recourse to thresholds; nevertheless a $B > 3$ or $< 1/3$ would usually be considered 'substantial'.

Results

Table 2 presents accuracy by age-group and block type for each memory condition and set size split by whether or not a change had actually occurred. Analyzing raw accuracy (i.e. correct/ incorrect) responses with standard techniques (such as ANOVA) can result in evidence for spurious interaction effects (Dixon, 2008). Therefore we applied a hierarchical generalized linear mixed effects model using a logit link function (see Jaeger, 2008). The details of this modelling are necessarily involved and, given that our main interest is in estimates of discriminability and bias, we present the full results of analyses of accuracy in the Supplementary Material. In summary, however, there was no indication that age-differences in change detection accuracy were larger for conjunction changes, nor was there any indication that mixing versus blocking different

[1]This was achieved using the `anovaBF` function from the `BayesFactor` package. The default settings were used with the exception that 'whichModels' was set to 'top', which compares a full model to reduced models omitting a specific component, and the number of MCMC iterations was set to 50,000. An additional 10,000 samples were taken until the proportional error for all comparisons was below 5%.

type of trial changed this.

Corrected recognition for Experiment 1 is presented in Figure 2A. Unsurprisingly the default Bayes factor analysis revealed overwhelming support for main effects of memory condition, set size, and age-group (all $B < 1/100$). By contrast the weight of evidence was against an overall effect of block type ($B = 5.19$, see Figure 2). Turning to interactions, specifically those including age-group, there was strong evidence for an interaction between age and set-size ($B = 0.0294$) which was qualified by substantial evidence for a three-way interaction with memory condition ($B = 0.308$). As can be seen in Figure 2 the drop in P_r associated with increasing the number of to-be-remembered items from 3 to 6 was less pronounced for the older group especially in the shape and binding conditions. Indeed when the analysis is conducted omitting the color condition the weight of evidence is against the three-way interaction ($B = 4.05$).

Crucially there was no suggestion in this data set that older adults were disproportionately less sensitive to binding changes; the reduced model omitting the age-group by condition interaction was favored over the full model by approximately 15-to-1 ($B = 15.51$). Further there was substantial evidence against modulation of this by block-type ($B = 4.8$). For the remaining interactions including age-group Bayes factors favored their omission from the full model (all $B > 3$).

Cowan et al. (2006) also found modulation of response bias, with older adults adopting a more conservative criterion for binding changes, leading to a greater miss rate. However, the same trends did not appear in the present data set (see Figure 2B). The data did not clearly favor the presence of an overall effect of age on bias over the null ($B = 1.68$) but there was good evidence against interactions between age-group and condition ($B = 11.56$), and the three way interaction with block type ($B = 5.24$). Tables of the full output of these, and subsequent, default Bayes factor analyses can be found in the Supplementary Material.

Discussion

In the literature on feature binding in VWM there has been little evidence to suggest that healthy older adults disproportionately struggle to detect changes to color-shape conjunctions relative to changes to these individual features (e.g. Brown et al., 2016; Rhodes et al., 2016). However, in these studies changes to individual features are presented in separate trial blocks to changes to feature binding. The findings of Cowan et al. (2006) suggest that mixing these trial types may in fact reveal a specific difficulty for older adults in discriminating conjunction changes, perhaps linked to a greater reliance on overall probe familiarity at test. Experiment 1 found no indication that mixing trial types specifically affected older adults' accuracy for detecting binding changes, in fact, it provided fairly strong evidence against this interaction.

There are a number of differences between our experiment and those of Cowan et al. (2006). For one, we assessed the binding between surface features, whereas they assessed the binding of color to location. Given previous suggestions that binding of what to where in VWM is a specific problem for older adults (Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Mitchell, Johnson, Raye, & D'Esposito, 2000; Borg et al., 2011), whereas surface feature binding is largely unaffected (Brockmole et al., 2008; Brown et al., 2016) we may expect the two to be differentially affected by experimental manipulation. However, as reviewed above, much of the early evidence for location binding deficits is questionable and subsequent research has been less clear (Read et al., 2016; Peterson & Naveh-Benjamin, 2016).

What may prove more important are the procedural differences between our and Cowan colleague's experiments. In fact there are good reasons to think that the paradigm used here is an improvement. Firstly, like Cowan et al. (2006) we had participants make a judgement on a single item, however, unlike their study we did not present un-probed items. Further we selected the colors for each memory array from a set of 8 *without* replacement. The presence of duplicated colors and un-probed items in the test array in the study of Cowan et al. (2006) may have acted as an additional cue as to whether a change had occurred and what kind of change could have occurred (see

Cowan et al., 2014). For color change trials in their study the probe was always unique, whereas for binding change trials the probe was always a duplicate. The present study, by avoiding duplicates and presenting a single item in the probe array, circumvents these potential confounds.

Secondly, in the present experiment, in addition to color-shape change trials, we included trials on which color or shape changed individually. This was the case in the experiments of Chen and Naveh-Benjamin (2012) who also found no effect of mixing item and binding changes. On the other hand, location was not constrained in the experiments of Cowan et al. and was never probed as an isolated feature, only in the combination of color and location (same location or location of a different test object). Including trials probing memory for both of the individual component features of a conjunction may be important as it ensures that participants are motivated to pay attention to each component feature equally (as a change is just as likely to occur for one feature as it is for the other). There is some evidence that attentional biases such as these to one component feature may be particularly harmful to older adults (Benjamin, Diaz, Matzen, & Johnson, 2012).

Therefore in a second experiment we assessed color-location binding using the same single probe paradigm deployed in Experiment 1, but with change trials for both component features. If mixing trial types specifically affects older adults' ability to detect color-location conjunction changes we should be able to demonstrate this, despite procedural modifications.

Experiment 2

This second experiment assessed color-location binding, as done in Cowan et al. (2006), in a situation where cues at test were minimized and incentive to pay attention to each component feature was equal, therefore resulting in a stronger test of an age-related binding deficit.

Method

Participants. Forty-eight younger adults were recruited from the student population of the University of Edinburgh and 49 healthy older adults were recruited from the Psychology research volunteer panel. None of these individuals had participated in Experiment 1. Participants were offered £5 in return for participation for the 45 minute session. Table 3 presents the demographic information of the participants split between the mixed and blocked conditions. Once again age-groups were well matched for years of education and the healthy older adults received higher estimates of verbal-IQ from the NART. All older adults scored 27 or above on the MMSE.

Stimuli and Apparatus. In Experiment 2 stimuli were defined by both color and location. Both colors and locations were selected from the sets described in Experiment 1. The locations were constrained to surround the center of the screen following an invisible circle (radius = 2.6°, see Figure 1C). As shape was irrelevant colors were presented in circles with a radius of approximately 0.5° of visual angle and separated center-to-center by at least 2°. Figure 1C gives examples of memory and test arrays in this experiment. In the probe display, the probe object could appear in a color not found in the array (color-change trials), a color found in the array could appear in a location not found in the array (location-change trials), a color previously found in the array could move to a location previously used for a different color (binding-change), or an object could appear exactly as before (no change).

Design and Procedure. The general design and trial procedure was identical to Experiment 1. Participants either saw different kinds of change trial (see Figure 1C) mixed together in the same block of trials or separately in their own trial-block.

Results

Accuracy across the experimental conditions of Experiment 2 is presented in Table 4. Once again the hierarchical logit model gave no strong indication of a disproportionate effect of age on the detection of conjunction changes. Further, there

was no evidence that mixing different trials led older adults to miss conjunction changes, as found by Cowan et al. (2006) (see Supplementary Material for full results).

Turning to our main outcome of interest, corrected recognition (P_r) for Experiment 2 is presented in Figure 3A. The Bayesian ANOVA, once again, revealed overwhelming evidence for effects of memory condition, set size and age (all $B < 1/100$). Also in line with Experiment 1 there was moderate evidence *against* an overall effect of block type ($B = 2.22$). For interactions including group, there was substantial evidence of an interaction between age and set size ($B = 0.2981$). In this experiment the overall age difference was larger at set size 6 relative to set size 3 and there was no-suggestion that this varied across memory conditions ($B = 3.051$). Most importantly omitting the age-group by memory condition interaction resulted in a model that was favored by more than 16-to-1 over the full model ($B = 16.32$) and there was strong evidence against the three-way interaction with probe type ($B = 11.1$).

The BANOVA marginally favored the exclusion of the three-way interaction between age, set size and memory condition ($B = 3.05$) and when contrasting color and binding conditions only the data favored neither the inclusion or exclusion of this component ($B = 1.28$). Assessing Figure 3 it appears that older adults were slightly less sensitive to binding changes at set size 3. Of course the evidence is indecisive in this respect but this general pattern is certainly not expected under an age-related binding deficit which would surely be compounded by increasing encoding and retention demands.

For the four-way interaction between all variables the data were not convincing either way ($B = 2.44$). As can be seen in Figure 3 this ambiguity appears to be driven by the performance of younger adults in the blocked location condition. There is a simple explanation as to why our younger group displayed a smaller set size effect in the location condition. As stimulus locations were selected from a restricted set, and participants in the blocked condition were aware of what kind of change was possible on a given trial, an appropriate strategy in the location only condition was to note the empty locations in the memory array; if, when the probe appeared, the locations were

still empty then there had been no change, whereas if one were occupied then a location change must have occurred. Using this strategy would make larger arrays easier as there are fewer empty locations to monitor. It is interesting to note that, overall, younger adults were more likely to note this aspect of the task as evidenced by their pattern of performance and post-experiment discussion with the researcher. Assessing such strategy difference between age-groups on working memory tasks will prove important in future work to separate out basic effects of healthy aging on binding mechanisms from difference in strategy use (see Peterson & Naveh-Benjamin, 2016, for this approach). In support of this proposal when location is omitted from the analysis, and only the color and binding conditions are contrasted, the evidence against the four-way interaction is slightly more convincing ($B = 3.03$).

Once again we assessed response bias (B_r) as Cowan et al. found more conservative responding for conjunction trials in older adults. This data is depicted in Figure 3B. There did not appear to be an overall effect of age on bias ($B = 0.22$) in the present experiment. Further there was strong evidence against the age by condition ($B = 18.33$) and age by condition by block type ($B = 12.87$) interactions (see Supplementary Material).

Discussion

Experiment 1 examined whether mixing color-shape conjunction change trials with changes to the individual components specifically affected older adults' ability to discriminate between old and new feature bindings. The results went against this suggestion. As the experiment of Cowan et al. (2006) assessed the binding of color and location, Experiment 2 used stimuli defined by these features instead. Again the results suggest that older adults have no specific problem in determining a change of color-location binding and that mixing these trials with changes to either color or location individually does not modulate this.

Thus rather than the *type* of binding being the crucial factor determining the differing findings of the present experiments and those of Cowan et al. we suspect that

another factor was at play in their finding of a specific deficit. As previously outlined, one potentially crucial factor may have been the omission of trials on which only location changed (which were included here) which may have incentivized participants to prioritize color. To assess this we ran an additional study with 24 younger and 24 older adults which was identical to Experiment 2 but with location change trials omitted. The results, described fully in the Supplementary Material, replicated the key findings of Experiment 2. Indeed the omission of the age by trial type (color change, binding change, no-change) interaction for P_r was favored in this data set by a factor of over 4-to-1. Thus it appears that the omission of location change trials, by itself, is not enough to reproduce the findings of Cowan et al. (2006).

We tentatively suggest that the findings of Cowan et al. (2006) can largely be put down to the presence of duplicates in the memory array and non-probed items in the probe array. In the Introduction we noted that in that study, the probed item in the color condition always was a unique color (whether or not it was changed from the studied array), whereas in the binding condition it was always a duplicate whether or not there was a change (see Cowan et al., 2014). In the blocked condition participants knew exactly which kind of change to expect and thus may have appreciated that in the binding condition, for example, it was sufficient to note only the repeated colors. Finally, an in-press correction of Cowan et al. (2006) reports that, due to an error, the binding deficit in their mixed-block experiment was smaller than was reported in the article.

It is clear that the use of a single probe without the presence of unprobed items is a better way of addressing the question of the efficacy of feature binding in healthy aging (see also, Read et al., 2016, for similar findings). If there were a true effect of mixing different trial types on the ability of older adults to discriminate binding changes the present paradigm should have shown this. On the contrary, three experiments (including an auxiliary experiment discussed above) have demonstrated no effect of mixing versus blocking trials.

General Discussion

Whether or not healthy aging affects the ability to temporarily maintain feature conjunctions in VWM is of both theoretical and practical importance. The magnitude of age differences increase greatly when participants are required to actively maintain visual information relative to verbal (see, e.g., Johnson et al., 2010) and it has been suggested that reduced feature integration across the adult life-span may account for some of this (Brockmole et al., 2008; Cowan et al., 2006; Sander et al., 2012). Further, there is growing evidence of a large feature binding deficit for surface features (e.g. shape and color) in early Alzheimer's disease, which may help distinguish this from healthy aging (e.g. Parra et al., 2010). Many studies, so far, suggest that there is no differential effect of healthy aging on the temporary retention of color-shape conjunctions (Brockmole et al., 2008; Brown et al., 2016; Isella et al., 2015; Rhodes et al., 2016). Also, while it has previously been proposed that binding to location may be a specific difficulty for older adults, a critical examination of the literature reveals that the initial evidence for this suggestion is underwhelming (Borg et al., 2011; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Mitchell, Johnson, Raye, & D'Esposito, 2000) and recent studies have been more equivocal on this issue (Pertzov et al., 2015; Read et al., 2016; Peterson & Naveh-Benjamin, 2016).

Cowan et al. (2006) reported that healthy older adults were much less able to detect changes to color-location binding when these trials were mixed with trials containing a change to color only relative to when these trial-types were blocked. If genuine this effect may reveal differences between younger and older adults in the use of familiarity based recognition in the change detection task or strategic differences when the type of possible change to prepare for is known. Experiment 1 assessed the effect of mixing versus blocking feature and conjunction changes for stimuli defined by color and shape. Overall accuracy gave no indication that older adults specifically struggled in detecting binding changes and block-type did not modulate this. Further analysis of corrected recognition as a measure of discriminability (Snodgrass & Corwin, 1988) provided strong evidence against a role of mixing trial types. Given the number of

methodological changes between Experiment 1 and the experiments of Cowan et al. (2006), in Experiment 2 we went on to assess whether we would find a role for mixing versus blocking with stimuli defined by color and location. Again, we found evidence against an overall age-related binding deficit and against any modulation by block-type. As argued above, it seems likely that procedural aspects, namely the inclusion of non-probed items and the use of duplicated colors, led to the appearance of an age-related binding deficit that does not generalize. A follow up experiment suggested that this discrepancy cannot be accounted for by the fact that in our experiments we included change trials for each of the component features alone and also served to replicate our main findings. Unlike previous investigations in this area, our measure of performance (corrected recognition) was chosen to provide a more accurate characterization of the discrimination underlying change detection with large changes between study and test (see Donkin et al., 2014; Rouder et al., 2008). This choice of measure, justified on the basis of previous research, and the converging analysis of raw accuracy and d', increases our confidence in the absence of the crucial interaction in these experiments.

Our findings regarding color-shape binding are in line with a growing literature that either fail to find a specific age-related binding deficit in VWM or provide evidence against one (Brockmole et al., 2008; Brown et al., 2016; Isella et al., 2015; Peterson & Naveh-Benjamin, 2016; Rhodes et al., 2016) and argue against the mixing of conjunction with feature changes as a boundary condition on this. In relation to the literature on binding to location in VWM, the results of Experiment 2 add to a mixed pattern of findings. As outlined in the Introduction, initial studies (Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Mitchell, Johnson, Raye, & D'Esposito, 2000) claimed to show that older adults struggle to detect changes to object locations in a 3 × 3 grid (see also Borg et al., 2011; Fandakova et al., 2014), however, the evidence to support this claim was either insufficient or not provided. What has followed has been a more varied pattern of findings with some failing to demonstrate a disproportionate effect of healthy aging on binding what was where in VWM (Pertzov et al., 2015; Read

et al., 2016) and others finding such an effect (Peterson & Naveh-Benjamin, 2016). Given the considerable methodological overlap between these studies and the present work the precise origin of this discrepancy is unclear; however the extant literature is not consistent with a large deficit where location is concerned (Peterson & Naveh-Benjamin, 2016).

Future work would benefit from a more nuanced treatment of location as a feature. For example, there is evidence to separate the categorical representation of location (i.e. that the red circle was located towards the bottom right) from more fine-grained coordinate level representations (Postma, Kessels, & van Asselen, 2008). In addition there is the well known distinction between allocentric, that is viewpoint independent, and egocentric, viewpoint dependent, spatial representation (O'Keefe & Nadel, 1978). It has been suggested that remembering where items are in allocentric space may be a more relational form of binding, where identity is bound to an external frame of reference (see Baddeley, Jarrold, & Vargha-Khadem, 2011, for discussion), in which case we may expect to observe an age-related deficit given older adults' well established problems with relational binding in both long-term memory (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008) and working memory (Chen & Naveh-Benjamin, 2012; Peterson et al., 2017). The simultaneous presentation of a memory array used here may foster a more egocentric representation, placing less demand on relational mechanisms. Further presenting all items at once may result in higher order structural representations of the overall properties or configuration of an array (Brady, Konkle, & Alvarez, 2011), which may be relatively preserved in normal aging (Olson et al., 2004). Of course we did not set out to manipulate the reliance on different frames of reference but this seems a fruitful area for further investigation.

Another area in need of further investigation is the distinction between relational and conjunctive forms of binding. In the literature as a whole there is generally a confound between the type of binding required and the type of material used. Studies assessing relational, or between-item, binding tend to use complex, meaningful material such as images of faces or scenes (e.g. Chen & Naveh-Benjamin, 2012), whereas studies

assessing conjunctive, or within-item, binding use basic features like color and shape (e.g. Brown et al., 2016). Recently, van Geldorp, Parra, and Kessels (2015) addressed this directly, using stimuli defined by color and shape, by either presenting these features as spatially separate items to be related or as unitized objects with the color filling the shape. In general older adults were poorer than younger and middle aged adults at recalling the pairings of features and crucially this did not appear to depend on the mode of presentation. This initial evidence suggests that maybe stimulus complexity is an important factor in some of the discrepant findings in the literature. However, it is clear that more research, in particular obtaining independent estimates of feature and binding memory, is needed on this topic. Simultaneous assessments of the different theoretical 'levels of binding' (Zimmer et al., 2006) such as these are required to better establish when older adults do and do-not struggle to bind information in working memory.

Our findings and review of the literature suggest that conjunctive binding mechanisms hold little promise in understanding the decline of working memory with age. So what potential mechanisms may be evoked to explain the pronounced overall effect of age observed on tasks like the one used here? Recent work has suggested that a deficit in top-down control of attention leads to older adults encoding more irrelevant information into working memory (see Sander et al., 2012, for a recent review). For example, Jost, Bryck, Vogel, and Mayr (2011) provide electrophysiological evidence (using the contralateral delay activity) that during the initial encoding of items in a change detection task, older adults were less able that younger adults to avoid attending to task irrelevant stimuli. In our experiment we did not manipulate the presence of distractor stimuli, however it is interesting to note that in the individual feature blocked conditions of our experiments it was beneficial to ignore the task irrelevant feature in favor of the task relevant one. The fact that we observed no modulation of the overall age effect on change detection performance by block type (mixed versus blocked) suggests that older adults did not struggle to do this kind of filtering. That being said another type of interference may be responsible for much of

the observed age effect; namely proactive interference (PI). In change detection tasks groups of younger adults have been found to make more false-alarms to items presented on recent trials, suggesting failure to update the contents of working memory from one trial to the next (Hartshorne, 2008; Makovski & Jiang, 2008). Indeed age differences in the ability to counter PI do appear to make a large contribution to age differences on working memory tasks, however age differences remain even in conditions of low PI (Bowles & Salthouse, 2003; Emery, Hale, & Myerson, 2008). The extent to which failure to update the contents of working memory trial-to-trial contributes to age-differences in change detection is an interesting avenue for future work.

Recent work employing paradigms that obtain more fine grained information from participant responses suggests that older adults' working memory representations are less precise. Older adults appear to require larger magnitude changes in order to accurately perform change detection tasks (Noack, Lovden, & Lindenberger, 2012) and tend to exhibit greater variability in recalling features following short delays (Peich et al., 2013; Pertzov et al., 2015). The stimuli used in change detection tasks are categorically distinct and for younger adults appear to be sufficient to support an all-or-nothing discrimination process (Donkin et al., 2014; Rouder et al., 2008). Nevertheless, it is not clear that this is also the case for older adults and future work should aim to address this. Thus the lower overall performance observed here and elsewhere (e.g. Brockmole et al., 2008; Brown et al., 2016; Cowan et al., 2006) may reflect difficulty in comparing the probe item to an internal representation distorted by noise (particularly in the shape condition of Experiment 1; see Figure 2A). In relation to the discussion of relational binding above, it is interesting to note that a neurocomputational model of age related memory change predicts that an increase in representational noise has a disproportionate effect on associative binding relative to the conjunctive form of binding, considered here (Li, Naveh-Benjamin, & Lindenberger, 2005).

It is important to note that there is substantial heterogeneity in the effects of aging on measures of working memory. Cross sectional studies have shown different

age-related trajectories across different aspects of working memory (Johnson et al., 2010; Park et al., 2002). For example, in a sample of over 95,000 participants, Johnson et al. (2010) found that a measure of digit span showed considerably less decline across adult aging than did a measure of memory for abstract visual patterns. Thus, conjunctive feature binding may not be the only working memory function left relatively unperturbed by the aging process. Probing why some functions are more susceptible than others holds great promise for our understanding of cognitive aging and cognition more generally (see Logie, Horne, & Pettit, 2015).

Finally there is inconsistency in the working memory literature regarding the efficacy of feature binding in general. In Experiment 1, relative to shape only, which was the most difficult individual feature condition, we found no performance cost to binding (see also Brown et al., 2016), however this is not always the case, as sometimes a clear binding cost is found (e.g. Allen et al., 2006; Peterson & Naveh-Benjamin, 2016). In fact, more detailed modeling of responses suggests that, actually, capacity for bindings is much smaller than capacity for individual features (Bays, Wu, & Husain, 2011; Cowan, Blume, & Saults, 2013). However, it is clear that there are factors mediating the magnitude of the binding cost. Likely candidates include the opportunity for verbal rehearsal of the to-be-remembered features, which may disproportionately benefit performance for individual features (Peterson & Naveh-Benjamin, 2016). In the present study we used stimuli deliberately constructed to minimize the influence of verbal recoding (Brockmole et al., 2008), arguably providing a better assessment of *visual* feature binding. The number of to-be-remembered items appears to be another important factor in the magnitude of the binding cost. Increasing the array size appears to increase the likelihood that memory representations will contain partial information (e.g., knowledge of color only and not shape, Cowan, Blume, & Saults, 2013). Further, while early work suggested that the number of to-be-remembered features per object had no effect on performance (Luck & Vogel, 1997), recent work clearly shows that adding additional feature-load increases the binding cost (Hardman & Cowan, 2015). Finally, it has been suggested that increasing the amount of time given to study objects

may allow individuals to engage elaborative encoding strategies that strengthen knowledge of feature combinations (Allen et al., 2006), although the evidence bearing on this is far from compelling (see Rhodes et al., 2016).

Conclusions

The present experiments followed up on the suggestion that mixing trials containing changes to features with those containing conjunction changes has a specific effect on older adults' ability to detect conjunction changes. For stimuli defined by both color-shape and color-location we found this not to be the case. Rather the data suggest that discrimination of binding changes is no more affected by healthy aging than the discrimination of changes to individual features.

References

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General*, *135*(2), 298–313.

Baddeley, A. D., Jarrold, C., & Vargha-Khadem, F. (2011). Working memory and the hippocampus. *Journal of Cognitive Neuroscience*, *23*(12), 3855–3861.

Bays, P. M., Wu, E. Y., & Husain, M. (2011). Storage and binding of object features in visual working memory. *Neuropsychologia*, *49*, 1622–1631.

Benjamin, A. S., Diaz, M., Matzen, L. E., & Johnson, B. (2012). Tests of the DRYAD theory of the age-related deficit in memory for context: Not about context, and not about aging. *Psychology and Aging*, *27*(2), 418–428.

Borg, C., Leroy, N., Favre, E., Laurent, B., & Thomas-Antérion, C. (2011). How emotional pictures influence visuospatial binding in short-term memory in ageing and Alzheimer's disease? *Brain and Cognition*, *76*(1), 20–25.

Bowles, R. P., & Salthouse, T. A. (2003). Assessing the age-related effects of proactive interference on working memory tasks using the rasch model. *Psychology and Aging*, *18*(3), 608–615.

Brady, T. F., Konkle, T., & Alvarez, G. A. (2011). A review of visual memory capacity: Beyond individual items and toward structured representations. *Journal of Vision*, *11*(5), 4. doi: 10.1167/11.5.4

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: a study of 55,753 participants aged 8–75. *Frontiers in Psychology*, *4*, 12. doi: 10.3389/fpsyg.2013.00012

Brockmole, J. R., Parra, M. A., Della Sala, S., & Logie, R. H. (2008). Do binding deficits account for age-related decline in visual working memory? *Psychonomic Bulletin and Review*, *15*(3), 543–547.

Brown, L. A., & Brockmole, J. R. (2010). The role of attention in binding visual features in working memory: Evidence from cognitive ageing. *The Quarterly Journal of Experimental Psychology*, *63*(10), 2067–2079.

Brown, L. A., Niven, E., Logie, R. H., Rhodes, S., & Allen, R. J. (2016). Visual feature binding in younger and older adults: Encoding and suffix interference effects. *Memory*.

Chen, T., & Naveh-Benjamin, M. (2012). Assessing the associative deficit of older adults in long-term and short-term/working memory. *Psychology and Aging*, *27*(3), 666–682.

Cowan, N., Blume, C. L., & Saults, J. S. (2013). Attention to attributes and objects in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 731–747.

Cowan, N., Donnell, K., & Saults, J. S. (2013). A list-length constraint on incidental item-to-item associations. *Psychonomic Bulletin & Review*, *20*(6), 1253–1258.

Cowan, N., Naveh-Benjamin, M., Kilb, A., & Saults, J. S. (2006). Life-span development of visual working-memory: When is feature binding difficult? *Developmental Psychology*, *42*(6), 1089–1102.

Cowan, N., Saults, J. S., & Blume, C. L. (2014). Central and peripheral components of working memory storage. *Journal of Experimental Psychology: General*, *143*(5), 1806–1836.

Craik, F. I. M., & Bialystok, E. (2006). Cognition through the lifespan: Mechanisms of change. *Trends in Cognitive Sciences*, *10*(3), 131–138.

Dixon, P. (2008). Models of accuracy in repeated-measures designs. *Journal of Memory and Language*, *59*(4), 447–456.

Donkin, C., Tran, S. C., & Nosofsky, R. (2014). Landscaping analyses of the ROC predictions of discrete-slots and signal-detection models of visual working memory. *Attention, Perception, & Psychophysics*, *76*(7), 2103–2116.

Dvorine, I. (1963). Quantitative classification of color blind. *Journal of General Psychology*, *68*, 255–265.

Ecker, U. K., Maybery, M., & Zimmer, H. D. (2013). Binding of intrinsic and extrinsic features in working memory. *Journal of Experimental Psychology: General*, *142*(1), 218–234.

Emery, L., Hale, S., & Myerson, J. (2008). Age differences in proactive interference, working memory, and abstract reasoning. *Psychology and Aging*, *23*(3), 634–645.

Fandakova, Y., Sander, M. C., Werkle-Bergner, M., & Shing, Y. L. (2014). Age differences in short-term memory binding are related to working memory performance across the lifespan. *Psychology and Aging*, *29*(1), 140–149.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal Psychiatric Research*, *12*, 189–198.

Gelman, A., & Stern, H. (2006). The difference between "significant" and "not significant" is not itself statistically significant. *The American Statistician*, *60*(4), 328–331.

Hardman, K. O., & Cowan, N. (2015). Remembering complex objects in visual working memory: do capacity limits restrict objects or features? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(2), 325–347.

Hartshorne, J. K. (2008). Visual working memory capacity and proactive interference. *PLoS one*, *3*(7), e2716.

Isella, V., Molteni, F., Mapelli, C., & Ferrarese, C. (2015). Short term memory for single surface features and bindings in ageing: A replication study. *Brain and Cognition*, *96*, 38–42.

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, *59*(4), 434–446.

Johnson, W., Logie, R. H., & Brockmole, J. R. (2010). Working memory tasks differ in factor structure across age cohorts: Implications for dedifferentiation. *Intelligence*, *38*, 513–528.

Jost, K., Bryck, R. L., Vogel, E. K., & Mayr, U. (2011). Are old adults just like low working memory young adults? Filtering efficiency and age differences in visual working memory. *Cerebral Cortex*, *21*, 1147–1154.

Keshvari, S., van den Berg, R., & Ma, W. J. (2013). No evidence for an item limit in

change detection. *PLoS Computational Biology*, *9*(2), e1002927.

Li, S. C., Naveh-Benjamin, M., & Lindenberger, U. (2005). Aging neuromodulation impairs associative binding neurocomputational account. *Psychological Science*, *16*(6), 445–450.

Logie, R. H., Horne, M. J., & Pettit, L. D. (2015). When cognitive performance does not decline across the lifespan. In R. H. Logie & R. G. Morris (Eds.), *Working memory and ageing* (pp. 21–47). Hove, East Sussex: Psychology Press.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Makovski, T., & Jiang, Y. V. (2008). Proactive interference from items previously stored in visual working memory. *Memory & Cognition*, *36*(1), 43–52.

Mitchell, K. J., Johnson, M. K., Raye, C. L., & D'Esposito, M. (2000). fMRI evidence of age-related hippocampal dysfunction in feature binding in working memory. *Cognitive Brain Research*, *10*(1), 197–206.

Mitchell, K. J., Johnson, M. K., Raye, C. L., Mather, M., & D'Esposito, M. D. (2000). Aging and reflective processes of working memory: Binding and test load deficits. *Psychology and Aging*, *15*(3), 527–541.

Morey, R. D., & Rouder, J. N. (2015). BayesFactor: Computation of Bayes Factors for Common Designs [Computer software manual]. Retrieved from `http://CRAN.R-project.org/package=BayesFactor` (R package version 0.9.11-1)

Naveh-Benjamin, M. (2000). Adult age differences in memory performance: Tests of an associative deficit hypothesis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *26*(5), 1170–1187.

Nelson, H. E. (1982). *National Adult Reading Test (NART): Test manual*. Windsor, UK: NFER-NELSON Publishing.

Nieuwenhuis, S., Forstmann, B. U., & Wagenmakers, E.-J. (2011). Erroneous analyses of interactions in neuroscience: a problem of significance. *Nature Neuroscience*, *14*(9), 1105–1107.

Noack, H., Lovden, M., & Lindenberger, U. (2012). Normal aging increases discriminal dispersion in visuospatial short-term memory. *Psychology and Aging*, *27*(3), 627–637.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford University Press.

Old, S. R., & Naveh-Benjamin, M. (2008). Differential effects of age on item and associative measures of memory: A meta-analysis. *Psychology and Aging*, *23*(1), 104–118.

Olson, I. R., Zhang, J. X., Mitchell, K. J., Johnson, M. K., Bloise, S. M., & Higgins, J. A. (2004). Preserved spatial memory over brief intervals in older adults. *Psychology and Aging*, *19*(2), 310–317.

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging*, *17*(2), 299–320.

Parra, M. A., Abrahams, S., Logie, R. H., & Della Sala, S. (2009). Age and binding within-dimension features in visual short-term memory. *Neuroscience Letters*, *449*, 1–5.

Parra, M. A., Abrahams, S., Logie, R. H., & Della Sala, S. (2010). Visual short-term memory binding in Alzheimer's disease and depression. *Journal of Neurology*, *257*(7), 1160–1169.

Parra, M. A., Della Sala, S., Logie, R. H., & Morcom, A. M. (2014). Neural correlates of shape–color binding in visual working memory. *Neuropsychologia*, *52*, 27–36.

Parra, M. A., Fabi, K., Luzzi, S., Cubelli, R., Hernandez Valdez, M., & Della Sala, S. (2015). Relational and conjunctive binding functions dissociate in short-term memory. *Neurocase*, *21*(1), 56–66.

Peich, M.-C., Husain, M., & Bays, P. M. (2013). Age-related decline of precision and binding in visual working memory. *Psychology and Aging*, *28*(3), 729–743.

Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of Neuroscience Methods*, *162*(1), 8–13.

Pertzov, Y., Heider, M., Liang, Y., & Husain, M. (2015). Effects of healthy ageing on precision and binding of object location in visual short term memory. *Psychology and Aging*, *30*(1), 26–35.

Peterson, D. J., & Naveh-Benjamin, M. (2016). The role of aging in intra-item and item-context binding processes in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, on-line ahead of print.

Peterson, D. J., Schmidt, N. E., & Naveh-Benjamin, M. (2017). The role of schematic support in age-related associative deficits in short-term and long-term memory. *Journal of Memory and Language*, *92*, 79–97.

Piekema, C., Rijpkema, M., Fernández, G., & Kessels, R. P. (2010). Dissociating the neural correlates of intra-item and inter-item working-memory binding. *PloS ONE*, *5*(4), e10214.

Postma, A., Kessels, R. P., & van Asselen, M. (2008). How the brain remembers and forgets where things are: The neurocognition of object–location memory. *Neuroscience & Biobehavioral Reviews*, *32*(8), 1339–1345.

R Core Team. (2015). R: A Language and Environment for Statistical Computing [Computer software manual]. Vienna, Austria. Retrieved from `http://www.R-project.org/`

Raz, N., & Rodrigue, K. M. (2006). Differential aging of the brain: patterns, cognitive correlates and modifiers. *Neuroscience & Biobehavioral Reviews*, *30*(6), 730–748.

Read, C. A., Rogers, J. M., & Wilson, P. H. (2016). Working memory binding of visual object features in older adults. *Aging, Neuropsychology, and Cognition*, *23*(3), 263–281.

Rhodes, S., Parra, M. A., & Logie, R. H. (2016). Ageing and feature binding in visual working memory: The role of presentation time. *The Quarterly Journal of Experimental Psychology*, *69*(4), 654–668. doi: 10.1080/17470218.2015.1038571

Rouder, J. N., Morey, R. D., Cowan, N., Zwilling, C. E., Morey, C. C., & Pratte, M. S. (2008). An assessment of fixed-capacity models of visual working memory. *Proceedings of the National Academy of Sciences*, *105*(16), 5975–5979.

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology*, *56*, 356–374.

Sander, M. C., Lindenberger, U., & Werkle-Bergner, M. (2012). Lifespan age differences in working memory: A two-component framework. *Neuroscience and Biobehavioral Reviews*, *36*, 2007–2033.

Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: applications to dementia and amnesia. *Journal of Experimental Psychology: General*, *117*(1), 34–50.

Staresina, B. P., & Davachi, L. (2010). Object unitization and associative memory formation are supported by distinct brain regions. *The Journal of Neuroscience*, *30*(29), 9890–9897.

van Geldorp, B., Parra, M. A., & Kessels, R. P. (2015). Cognitive and neuropsychological underpinnings of relational and conjunctive working memory binding across age. *Memory*, *23*(8), 1112–1122.

Yang, X., Goh, A., Chen, S.-H. A., & Qiu, A. (2013). Evolution of hippocampal shapes across the human lifespan. *Human brain mapping*, *34*(11), 3075–3085.

Zimmer, H. D., Mecklinger, A., & Lindenberger, U. (2006). Levels of binding: types, mechanisms, and functions of binding in remembering. In H. D. Zimmer, A. Mecklinger, & U. Lindenberger (Eds.), *Handbook of binding and memory: perspectives from cognitive neuroscience* (pp. 3–22). New York, NY: Oxford University Press.

Table 1

Participant characteristics for Experiment 1

	Blocked		Mixed	
	Younger	Older	Younger	Older
N	24	24	24	25
N_{Female}	17	17	14	18
Mean Age (SD)	20.708 (2.896)	70.958 (5.614)	21.125 (2.659)	70.280 (4.430)
Years of Education	16.104 (2.613)	17.062 (2.898)	16.521 (2.164)	15.960 (2.428)
NART Verbal IQ	111.915 (5.564)	121.225 (4.264)	111.298 (7.142)	118.690 (5.756)
MMSE	-	29.333 (0.761)	-	29.600 (0.816)

Table 2

Accuracy accross age-groups and experimental factors for Experiment 1

			Blocked		Mixed	
			Younger	Older	Younger	Older
Change	Color	3	0.924 (0.026)	0.828 (0.027)	0.966 (0.008)	0.932 (0.015)
		6	0.805 (0.024)	0.693 (0.026)	0.917 (0.018)	0.762 (0.036)
	Shape	3	0.740 (0.032)	0.586 (0.039)	0.737 (0.023)	0.630 (0.034)
		6	0.635 (0.034)	0.547 (0.035)	0.714 (0.030)	0.623 (0.039)
	Binding	3	0.750 (0.026)	0.596 (0.035)	0.742 (0.033)	0.620 (0.028)
		6	0.742 (0.031)	0.659 (0.044)	0.734 (0.028)	0.595 (0.039)
No-Change	Color	3	0.906 (0.021)	0.794 (0.039)	0.858 (0.018)	0.745 (0.025)
		6	0.690 (0.029)	0.555 (0.050)	0.510 (0.022)	0.527 (0.026)
	Shape	3	0.797 (0.029)	0.758 (0.031)	-	-
		6	0.620 (0.023)	0.594 (0.042)	-	-
	Binding	3	0.844 (0.031)	0.721 (0.035)	-	-
		6	0.508 (0.028)	0.521 (0.042)	-	-

Note: Standard errors are given in parenthesis. The mixed condition results in one accuracy estimate per set size for no change trials.

Table 3

Participant characteristics for Experiment 2

	Blocked		Mixed	
	Younger	Older	Younger	Older
N	24	25	24	24
N_{Female}	18	16	17	17
Mean Age (SD)	20.708 (2.528)	70.000 (4.770)	21.125 (1.727)	71.417 (4.671)
Years of Education	16.021 (1.992)	16.420 (2.929)	16.625 (1.583)	16.583 (3.847)
NART Verbal IQ	108.448 (4.059)	119.420 (3.590)	108.875 (5.707)	119.325 (5.293)
MMSE	-	29.320 (0.852)	-	29.500 (0.933)

Table 4

Accuracy accross age-groups and experimental factors for Experiment 2

			Blocked		Mixed	
			Younger	Older	Younger	Older
Change	Color	3	0.948 (0.013)	0.925 (0.015)	0.950 (0.010)	0.882 (0.028)
		6	0.820 (0.022)	0.725 (0.036)	0.823 (0.025)	0.700 (0.037)
	Location	3	0.924 (0.031)	0.900 (0.026)	0.958 (0.011)	0.855 (0.026)
		6	0.917 (0.027)	0.790 (0.029)	0.905 (0.019)	0.797 (0.027)
	Binding	3	0.919 (0.017)	0.812 (0.043)	0.912 (0.022)	0.828 (0.032)
		6	0.826 (0.018)	0.713 (0.035)	0.805 (0.030)	0.718 (0.037)
No-Change	Color	3	0.930 (0.014)	0.890 (0.030)	0.899 (0.014)	0.872 (0.023)
		6	0.740 (0.027)	0.647 (0.035)	0.662 (0.018)	0.648 (0.024)
	Location	3	0.932 (0.013)	0.877 (0.018)	-	-
		6	0.810 (0.024)	0.667 (0.045)	-	-
	Binding	3	0.927 (0.018)	0.873 (0.022)	-	-
		6	0.654 (0.027)	0.613 (0.037)	-	-

Note: Standard errors are given in parenthesis. The mixed condition results in one accuracy estimate per set size for no change trials.

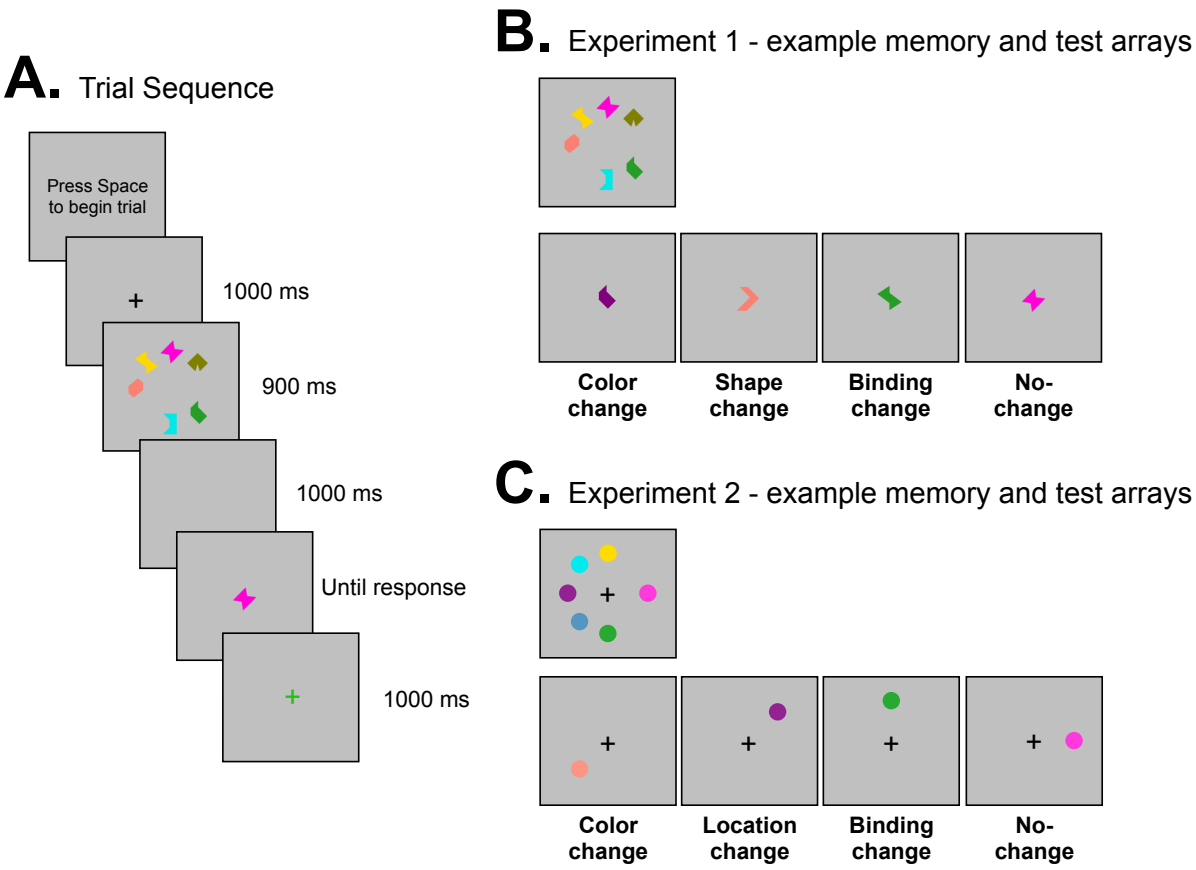

Figure 1. Illustration of the trial sequence (A) and examples of memory and test arrays for Experiments 1 (B) and 2 (C).

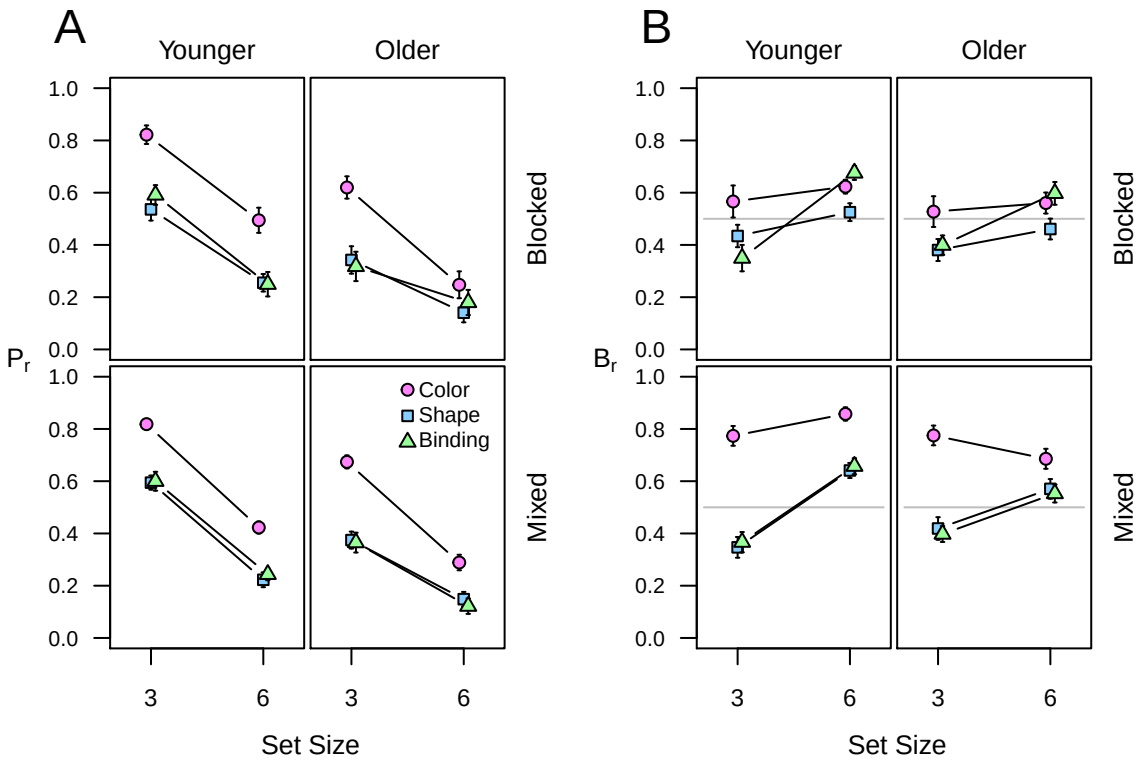

Figure 2. Estimates of corrected recognition, P_r (A), and bias, B_r (B), across age-groups and block types for Experiment 1. Error bars denote ± standard error.

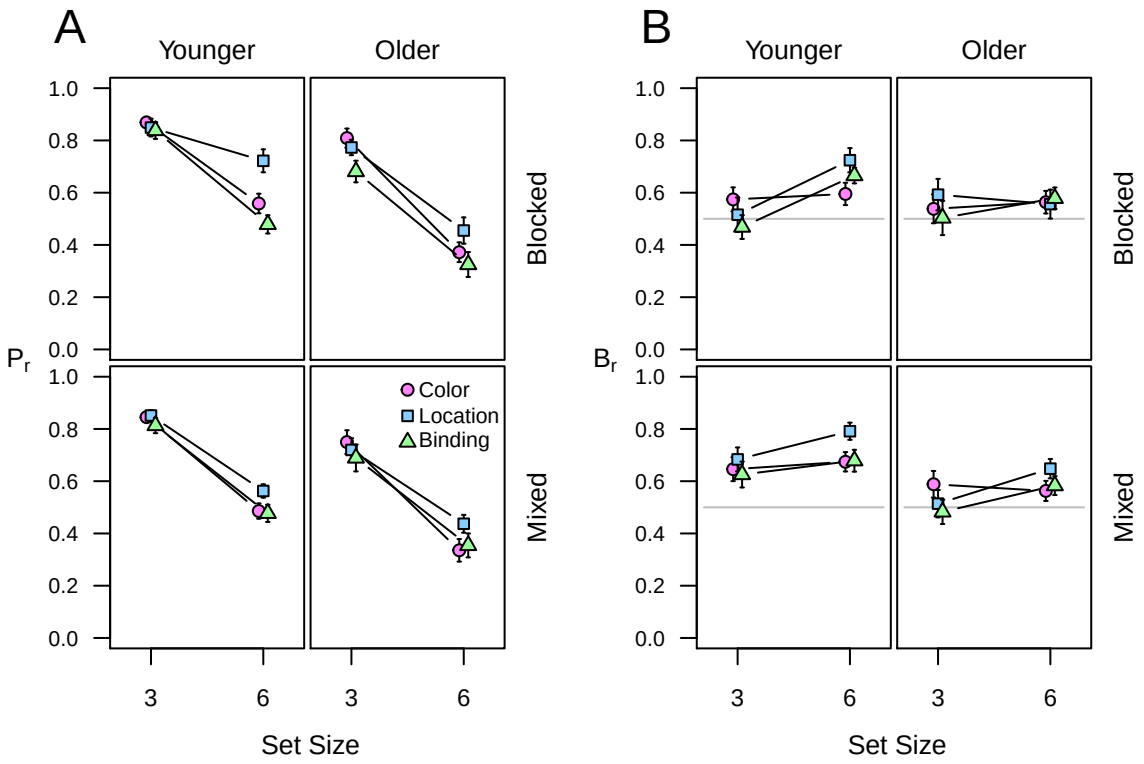

Figure 3. Estimates of corrected recognition, P_r (A), and bias, B_r (B), across age-groups and block types for Experiment 2. Error bars denote ± standard error.